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## Quantifying meniscal kinematics in dogs

Park, Brian H ; Banks, Scott A ; Pozzi, Antonio

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1                   **Quantifying Meniscal Kinematics in Dogs**

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8                   **Author Contributions:** (a) Designed experiments, (b) conducted experiments,  
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19                  **Running Title:** Quantifying meniscal kinematics

## Abstract

The dog has been used extensively as an experimental model to study meniscal treatments such as meniscectomy, meniscal repair, transplantation and regeneration. However, there is very little information on meniscal kinematics in the dog. This study used MR imaging to quantify in vitro meniscal kinematics in loaded dog knees in four distinct poses: extension, flexion, internal and external rotation. A new method was used to track the meniscal poses along the convex and posteriorly tilted tibial plateau. Meniscal displacements were large, displacing 13.5 mm and 13.7 mm posteriorly on average for the lateral and medial menisci during flexion ( $p = 0.90$ ). The medial anterior horn and lateral posterior horns were the most mobile structures, showing average translations of 15.9 mm and 15.1 mm, respectively. Canine menisci are highly mobile and exhibit movements that correlate closely with the relative tibiofemoral positions.

*Keywords: Meniscus, MRI, Dog, Meniscal kinematics, Meniscus translation*

## Introduction

The menisci of the knee are crescent-shaped structures that contribute to load distribution, lubrication, and stability of the tibiofemoral joint [1-3]. Because of their unique geometry, the menisci improve congruity and protect the articular cartilage by minimizing contract stress by maximizing contact area between the femoral and tibial condyles. Its been estimated that 50% - 70% of the body weight is transmitted through the menisci during full extension and increases to 85% - 90% in flexion [4,5]. The menisci are dynamic structures and as the knee flexes, they need to be able to move as the femur and tibia move to maintain maximum congruency. The kinematics of menisci are of particular interest, and have been demonstrated in experimental studies on human knees [4-18]. One of the unique characteristics of the menisci is their complex system of attachments to tibia and femur [19-23]. The function of the meniscal ligaments is multifold. These ligaments prevent extrusion of the menisci during load but also guide these structures during knee motion. In dogs, the medial meniscus is attached to the tibia by both the anterior and posterior meniscotibial ligament. Similarly the lateral meniscus is attachment to the tibia by the meniscotibial ligaments, but on the posterior side it is more firmly attached to the femur by the posterior mensicofemoral ligament which is thicker than the posterior mensicotibal ligament [19,20,23].

Many researchers have investigated both human and animal meniscal kinematics in the past, but there remains a lack of robust evidence regarding meniscal translation in the healthy knee for comparative purposes [18]. This

information may be valuable for comparative purposes because the dog has been extensively used as an experimental model to study meniscal treatments such as meniscectomy, meniscal repair, transplantation and regeneration [24-33]. However, the authors were unable to locate studies reporting meniscal kinematics in dogs at the time of study initiation.

The present study was performed to provide a three-dimensional (3D) description of meniscal kinematics of intact, loaded cadaveric stifles at full flexion and extension, along with tibial internal and external rotation applied at 45° ~~degrees~~ flexion. Four poses were analyzed for each knee. The meniscal kinematics were analyzed using 3D models reconstructed from 3T MRI taken at both sagittal and coronal views. We hypothesize that meniscal kinematics in dogs are similar to what's been previously reported in cadaveric human studies. Specifically, we hypothesize that as the knee flexes, 1) the menisci translate in the posterior direction, 2) the lateral meniscus translates posteriorly with flexion more than the medial meniscus, and 3) the anterior horns of the meniscus will show more displacement than the posterior for both menisci.

## **Material and methods**

### *Experimental Animals*

This study was approved by the University of Florida Institutional Animal Care and Use Committee (# 20130788). Sixteen intact hind limbs (n=32 menisci) were collected from 16 dogs (range of body weight 20-35 Kg) that were euthanized for reasons unrelated to this study. Dogs were selected primarily for healthy joints

and body weight, resulting in inclusion of four breeds. The dogs were skeletally mature and without apparent signs of stifle disease confirmed during anatomical dissection. The skin and regional musculature were dissected and removed from the limbs. Both femur and tibia were sectioned 12 cm above and below the joint, to prepare each intact stifle with consistent lengths of femur and tibia. A transepicondylar k-wire was drilled through the femur and tibia under fluoroscopic guidance to allow mechanical loading and the k-wire was replaced with a carbon-fiber rod for MR compatibility. (Figure 1).

#### *Experimental Design*

Prior to MR imaging, each stifle was placed into a nonmetallic loading jig that provided a fixed flexion angle and applied a compressive load across the joint (Figure 1). To approximate in vivo conditions of a 30kg dog in a standing position, a static axial load of 30% body weight (98N) was applied [34,35]. The load was applied along the long axis of the tibia with two elastic bands on the medial and lateral aspects of the joint. The band displacement required to develop 49N tension was calibrated with a MTS machine every time prior to set up. Stress-relaxation tests showed there was less than 2N variation in elastic band tension over a 30-minute test modeling the MR scan time. The knees were placed at four different positions to simulate the full range of knee flexion during daily activities [36]: 145° flexion, 30° flexion, and 45° flexion with tibial internal and tibial external rotation. A ten-minute hold was observed after compressive load application to allow the specimens to reach equilibrium. MR imaging was then conducted with only a few minutes interval between each of the four poses

during specimen repositioning. For the third and fourth joint poses, an additional elastic band was applied to the tibia with sufficient torque to achieve maximum internal and external rotation. Specimens were kept hydrated during the entire MR imaging process by wrapping them in wet towels once thawed.

#### *MRI Protocols*

Intact stifles were thawed prior to imaging and scanned with the 3.0T MR system using a PD sequence (TR/TE/FA, 4210/25/90; FOV, 120mm; matrix, 512x512, slice thickness/gap, 2mm/0mm). All images were stored on a picture archive and communication system (PACS) in digital imaging and communications in medicine (DICOM) format.

#### *Segmentation*

All 3D reconstructions were done manually by a single observer using open-source software (ITK SNAP, [www.itksnap.org](http://www.itksnap.org))[37]. Both menisci, tibia, fibula, and a cylindrical hole on the tibia drilled for mechanical loading were reconstructed for every knee (n = 64). Model post processing was done using the alpha shape algorithm (MATLAB R2014b, MathWorks, Natick, Massachusetts, U.S.A), segmented contours were meshed with triangles to create smooth 3D models much more similar to the real meniscus (Geomagic Studio, Figure 2). All models from right limbs were mirrored as left limbs to permit direct comparisons.

#### *Kinematic Analysis*

First, an anatomical coordinate system for the tibia was set by performing a rigid body registration with a representative tibia model aligned in the desired anatomical coordinate system [38]. The segmented meniscal models were then

aligned in the standardized tibial reference frame by registering the transverse carbon fiber rod and fibular anatomic features (which are invariant geometric features). The process was repeated for models from all flexion angles (145°FLX, 30°FLX, internalINT and EXT-external rotation at 45°FLX). Second, we took advantage of the fact the tibial condyles are very well approximated by cylinders to construct a size-independent measurement of meniscal translation: meniscal translations were determined using angular coordinates. Cylinders were fit to the inferior surfaces of the medial and lateral menisci for all stifle poses. The central axes of the cylinders were aligned with the medial/lateral axis of the tibia (global z-axis, Figure 3A,B). How well the cylinders fit the distal meniscal surfaces was quantified as the root mean squared (RMS) distances between the two surfaces. Third, each meniscus was represented by 10 three-dimensional points (5 points on the anterior horn, 5 points on the posterior horn, determined as sagittal-slice area centroids evenly spaced in the mediolateral direction) in each joint pose (Figure 3C). Fourth, the location of the ten meniscal points were expressed as angles measured clockwise from the most posterior point on the cylinder (Figure 3D). Overall meniscal translations were calculated by observing the translation of the centroid of the medial and lateral meniscus at different poses. These translations were expressed as angles relative to the reference cylinder, and also as linear displacements for an average cylinder radius (displacement = radius\*angle).

#### *Statistical analysis*



All measurements for significance were calculated using a one-way ANOVA with alpha of 0.05. The displacement measurements for the entire meniscus centroid from full extension and full flexion were compared. The translations of anterior and posterior horn points were also compared. All statistical calculations were performed using Microsoft Excel.

## Results

All knees showed normal soft tissue, bone, ligament and meniscus anatomy in the MRI, which also was confirmed after dissection. RMS errors for fitting cylindrical surfaces to the inferior meniscal surfaces were less than 0.6 mm for the medial and 1.0 mm for lateral meniscus. All meniscal measurements were calculated by taking the average of the 10 points representing both anterior and posterior horns and are shown in both arc angles (in degrees) and in arc length (in millimeters, Figure 4). Meniscal movements for different poses are expressed relative to their positions in full extension (30 degrees flexion, Table 1).

Our first hypothesis is accepted while the second is unsupported. Both menisci displayed similar patterns of posterior translation with flexion, with the medial meniscus moving slightly more than the lateral in the posterior direction during flexion but showing no significant differences ( $p=0.89$ ). Out of 16 specimens, 7 had greater medial than lateral posterior translations, 8 had greater lateral than medial posterior translations, and one specimen had medial and lateral translations within 0.01 mm.

Our third hypothesis is rejected. During flexion, the lateral posterior horn was more mobile than the anterior horn ( $p = 0.019$ ) while the medial anterior horn tended to be more mobile than the posterior horn (not significant,  $p = 0.371$ , Table 1, Figure 4). When tracking meniscal centroids, both medial and lateral menisci moved posteriorly with flexion by similar amounts ( $p = 0.90$ ), while tibial external rotation induced anterior translation of the lateral meniscus and posterior translation of the medial meniscus. Tibial internal rotation induced translations opposite to those observed with external rotation.

## Discussion

The objective of this study was to describe the meniscal kinematics of the intact dog knee at different flexion angles using a novel method to track the meniscal poses along the convex and posteriorly sloped tibial plateau. Ex vivo knee specimens were loaded to simulate weight bearing forces and positioned over their normal envelope of motion: full flexion, full extension, and internal and external rotation at 45° flexion. As expected, both menisci translated posteriorly with flexion (Hypothesis 1), but the patterns of motion were different than expected (Hypotheses 2 and 3).

The human tibial plateau is relatively flat, making it convenient and intuitive to describe meniscal motions as linear displacements on the plane approximating the tibial surface [4-18]. The canine tibial plateau is highly convex and more posteriorly sloped than in humans, and canine menisci move significantly in both the anterior/posterior and superior/inferior directions [39-44].

The measurement method presented in this study allowed us to account for the different surface geometry of the lateral and medial tibial plateau and to provide measures that were unaffected by differences in joint size. A similar approach has been used in human studies tracking articular contact locations along the surface of the femoral condyles during movement [47,48].

Studies of human knees agree that both menisci translate posteriorly as the knee goes from extension to flexion. However, there is little consensus on the magnitudes of meniscal displacements *in vitro* or *in vivo*. *In vitro* studies uniformly report greater lateral than medial meniscal displacements [8-10], but *in vivo* studies have reported both greater medial [11-14] and greater lateral [15-17] translations. Our results are similar, finding roughly equivalent numbers of knees with greater medial than lateral, and knees with greater lateral than medial displacements. Variation in reported meniscal kinematics is likely attributable to differences in measurement techniques, experimental procedures and set-up, and the use of different MRI protocols. Differences between canine and human meniscal kinematics could result from variations in meniscal shapes [49], meniscomfemoral attachments [19,50] and anterior insertions [51]. Kinematic variation within our data may be due, in part, to four breeds being included in the study specimens.

The most significant finding in our study is the large magnitude of meniscal translations during flexion, averaging more than 13 mm in both menisci. These are larger absolute translations than have been reported for human meniscal translations (11.6 mm for medial anterior horn [7], 8.3 mm [17] and 5.6

mm – 9.5 mm [18] for the lateral meniscus), and represent much greater relative translations in the small canine knee. The large magnitude of meniscal translation measured in our study may depend on the roll-back of the femur, which may be more pronounced in dogs than in people because of the geometry of the tibial plateau. The dog has more convex [41-45] and posteriorly sloped [19,42] tibial condylar articular surfaces than humans, and very different radii of curvature between lateral and medial compartments on the tibia [43] and femur [45]. Posterior translation of the femoral condyles with flexion is influenced by the shapes of the femoral and tibial condyles [46,48]. The more concave medial tibial condyle in the human knee may be responsible for the minimal translation reported in weight bearing and non weight bearing kinematics [52]. In contrast, the convex shapes of the canine tibial condyles may lead to a marked backward rolling of the femoral condyle and consequently large meniscal translations.

Our methodology allowed describing the motion of each meniscal horn, indicating that meniscal kinematics cannot be reported as whole meniscus translation, but rather as a complex change in shape of this fibrocartilage structure. As an example, when using meniscal centroids for the calculation of motion during flexion, both medial and lateral menisci moved posteriorly by similar magnitude. However, using the ten tracking points instead of the centroid, the lateral posterior horn was found more mobile than the anterior horn while the medial anterior horn tended to be more mobile than the posterior horn during flexion. These different motions patterns of the anterior and posterior horns may result from the coupled motion between axial rotation and flexion, also known as

screw-home mechanism, described in both human and canine knees in vivo [28, 53].

As expected from the canine anatomy of the meniscal attachments, the lateral posterior horn was more mobile than the anterior horn while the medial anterior horn tended to be more mobile than the posterior horn. In dogs there is a strong menisco-femoral ligament, which is analogous to the human anterior menisco-femoral ligament and a thin meniscotibial connection [19]. This firm attachment to the femoral condyle is likely responsible for greater mobility of the posterior horn during motion of the lateral condyle. In contrast, the posterior horn of the medial meniscus is strongly attached to the tibial plateau through a large posterior ligament and a strong attachment to the medial collateral ligament, which limit its mobility. Our data confirm that the low incidence of tears of the posterior horn of the lateral meniscus may be explained by its greater mobility than the posterior horn of the medial meniscus [54].

The primary limitation of our study is that it was performed in-vitro. Practically, this was the only method that allowed precise positioning and loading of the joints to obtain images relevant to ambulatory conditions. Additionally, because very few studies of canine meniscal mechanics have been reported it is difficult to perform a direct comparison of our results to previous work. We also only observed four knee postures with a single joint compressive load, so we cannot comment on the entire gamut of possible meniscal motions in dog knees. The compressive load in each joint was applied parallel to the long axis of the tibia using the calibrated stretch of elastic bands. Slocum et al. theorized that,

271 during weight bearing, the joint reaction force is approximately parallel to the  
272 longitudinal axis of the tibia [55]. Thus our approach may represent a meaningful  
273 range of weight bearing conditions during different daily activities. Our crude  
274 method of applying forces to the joint was simple and MR-compatible. The goal  
275 of applying joint forces was simply to move the joint to a boundary of the slack  
276 region with a relevant level of joint compression. Thus, the specific applied joint  
277 load probably had little effect on the observed kinematics. Still, we attempted to  
278 apply loads that were physiologically relevant, and we double-checked elastic  
279 band displacements before and after imaging to ensure, to the degree possible,  
280 the loading was consistent and maintained throughout imaging. A considerably  
281 more complex and capable mechanism will be required to accurately apply  
282 forces over the entire range of physiologic joint loads in a similar MR setup.

283 In conclusion, this study presents normal weight bearing meniscal  
284 kinematics in dog knees. We report a new technique for quantifying meniscal  
285 translation that allowed us to account for the different surface geometry of the  
286 lateral and medial tibial plateau, and to provide measurements that were  
287 unaffected by differences in joint size. This new measurement technique may be  
288 helpful in quantifying meniscal translations for all species with high tibial plateau  
289 angles, similar to dogs, to obtain better representation of the meniscus moving in  
290 multiple directions. Our data indicates much greater meniscal motions in dogs  
291 than in humans, with both menisci moving posterior equally during flexion. Dog  
292 knees are commonly treated clinically for meniscal pathologies and often are  
293 used as translational study models for human knee treatments, so we are

294 hopeful our data will provide useful observations of normal meniscal mechanics  
295 in dogs.

296

297

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301 Committee (IACUC) at the University of Florida. IACUC protocol number is  
302 201307888, and the approval was given by IACUC chair, William Buhi.

303

#### 304 **Conflict of Interest**

305 None of the authors have a conflict of interest regarding this study.

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### Figure Legends

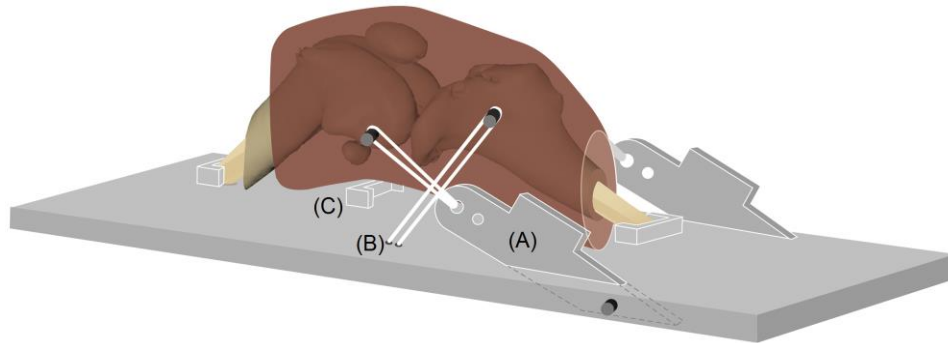


Figure 1: Specimens were attached to a knee-loading jig made from MR-compatible non-ferrous materials. Elastic bands applied between the femur, tibia and the base allowed application of joint compression and axial rotation loads. (A) – Stretch of the elastic bands was set to apply 49N of forces, and applied to both sides of the femur for a net force of 98N across the joint. (B) – Elastic bands attached to the tibia were for application of torques for tibial rotations. (C) – The jig allowed the joint to be positioned at flexion angles of 145°, 30° and 45° for tibial external and internal rotation.

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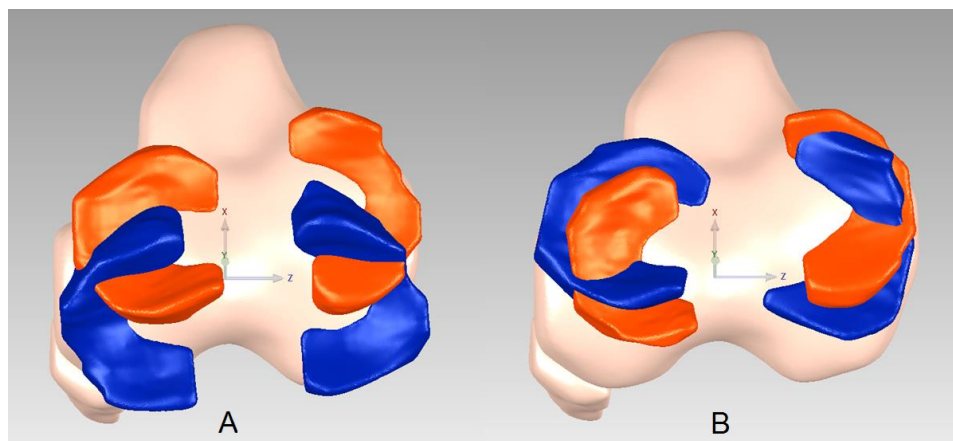


Figure 2: Images of the segmented menisci are superimposed on a left tibia model, with the anatomical coordinate systems shown. A - The menisci at 30 degrees flexion are shown in orange while at 145 degrees flexion are shown in blue. B – The menisci at full tibial internal rotation are shown in orange and full tibial external rotation shown in blue, both captured at 45 degrees flexion.

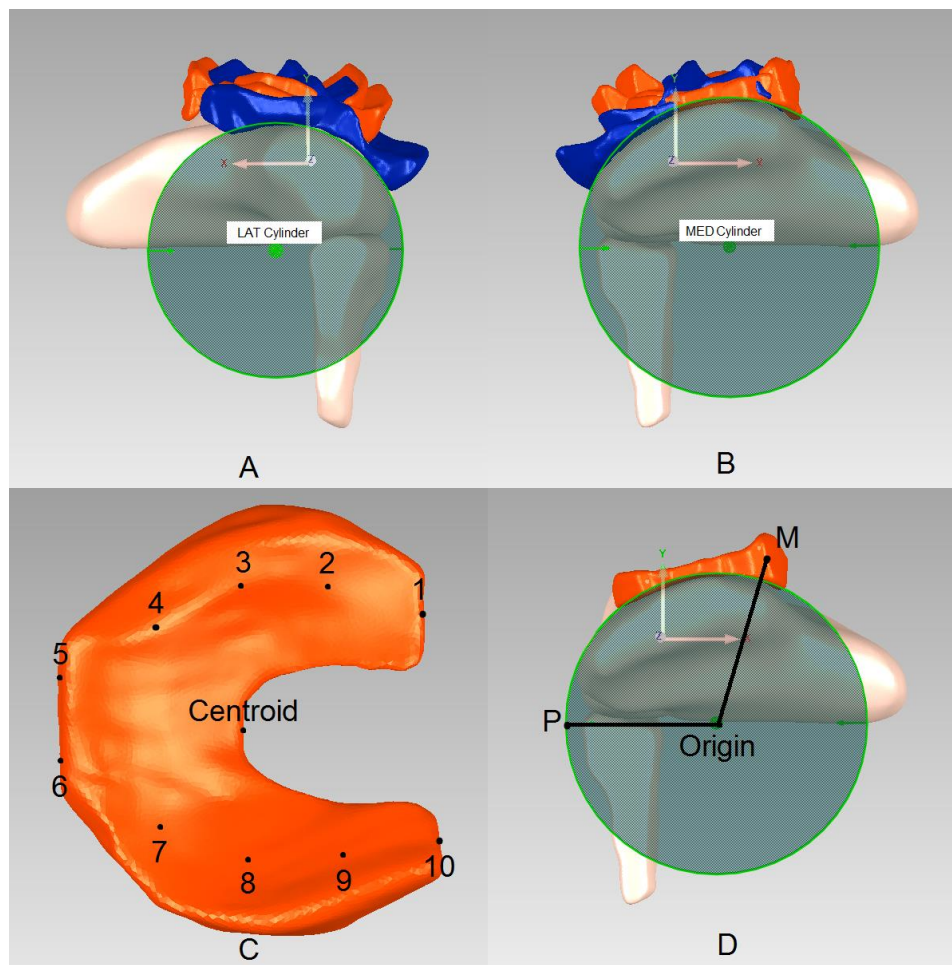


Figure 3: Sagittal views of the segmented tibia/fibula and menisci with fitted cylinders superimposed. A – Lateral image. B – Medial image. C – Ten points used to represent the meniscus for all measurements. D – Image of the medial knee showing the angle measurement from the most posterior point of the cylinder (P) to the selected meniscal point (M).

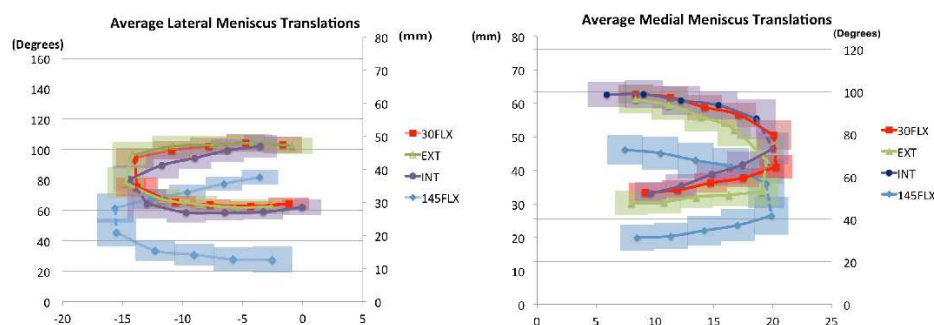


Figure 4: Average medial and lateral meniscal translations for four knee poses. Each point represents the average position of that meniscal cross-section for all knees. The vertical axes represent sagittal plane translation while the horizontal axes show mediolateral displacements. Shaded areas represent  $\pm 1$  standard deviation.



569 Table 1: Lateral and medial meniscus movements relative to 30° flexion (full  
570 extension). Anterior/Posterior direction is represented by positive/negative  
571 values.

<u>Joint Posture</u>	<u>Segment</u>	<u>Lateral displacement (mm)</u>	<u>Medial displacement (mm)</u>
<u>145° Flexion</u>	<u>Anterior horn</u>	<u>-12.9* (2.7)</u>	<u>-15.9 (6.4)</u>
	<u>Posterior horn</u>	<u>-15.1 (2.5)</u>	<u>-14.1 (4.8)</u>
	<u>Meniscus centroid</u>	<u>-13.5 (2.7)</u>	<u>-13.7 (4.8)</u>
<u>Tibial External Rotation</u>	<u>Anterior horn</u>	<u>0.6 (2.2)</u>	<u>-3.6 (4.2)</u>
	<u>Posterior horn</u>	<u>0.3 (2.1)</u>	<u>-4.6 (4.0)</u>
<u>Tibial internal Rotation</u>	<u>Anterior horn</u>	<u>-3.3 (2.9)</u>	<u>2.6 (3.2)</u>
	<u>Posterior horn</u>	<u>-2.7 (2.8)</u>	<u>2.9(3.5)</u>

\* p<0.05, less anterior horn than posterior horn displacement.